Water Quality Monitoring of Candlewood Lake & Squantz Pond 2021

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For the Communities of Brookfield, Danbury, New Fairfield, New Milford, and Sherman

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Introduction

The Candlewood Lake Authority

Candlewood Lake is a pumped storage reservoir built in the late 1920's for the purposes of power generation. It has since become a premier destination for lake recreation in both Connecticut and the New York City tristate area and is a critical economic and environmental asset for local communities. The Candlewood Lake Authority (CLA) is an organization formed from ordinances by the municipal governments of Brookfield, Danbury, New Fairfield, New Milford, and Sherman pursuant Connecticut General Statute §7-151a, to enforce boating law on the water and to provide lake management to protect and conserve the environmental value of Candlewood Lake and Squantz Pond. Those 5 municipalities equally share a substantial amount of the responsibility for much of the CLA's operational budget. FirstLight Power, the owners and operators of Candlewood Lake and its hydropower generation have also historically made a voluntary contribution to the Candlewood Lake Authority's budget. Annual donations, grants, and fundraising projects constitute the final substantial portion of the Lake Authority's budget.

Candlewood Lake Authority Mission Statement

The Candlewood Lake Authority provides lake, shoreline, and watershed management to foster the preservation and enhancement of recreational, economic, scenic, public safety and environmental values of the Lake for the City of Danbury and the Towns of Brookfield, New Fairfield, New Milford, and Sherman in cooperation with the State of Connecticut and the hydro power owner of the lake.

Lake and Watershed Characteristics

Candlewood Lake is Connecticut's largest, with a surface area of roughly 5,064 acres. The Candlewood Lake & Squantz Pond shared watershed is approximately 25,907 acres and contained almost entirely in the Connecticut municipalities of Brookfield, Danbury, New Fairfield, New Milford, and Sherman. (Jacobs and O'Donnell 2002). New Fairfield and Sherman contain 73% of the watershed, while a small portion crosses the border into New York State (Table 1).

Town	Acres of Watershed	% Of watershed within municipal boundary	% Of municipality within watershed boundary
Brookfield	1,177	4	9
Danbury	2,726	10	10
New Fairfield	12,197	46	72
New Milford	2,629	10	6
Sherman	7,132	27	51
New York State	600	3	
Total	26,461		

Table 1*: Percentages of the Candlewood Lake & Squantz Pond watershed contained within each bordering municipality, and the percentage of each municipality contained within the watershed.*

Squantz Pond has a surface area of roughly 270 acres, with a watershed of 3,662 acres contained entirely within the borders of Sherman and New Fairfield, making it a sub-basin of the Candlewood Lake watershed. A culvert below the Route 39 causeway in New Fairfield connects the two hydrologically, allowing free water flow between Candlewood Lake and Squantz Pond.

The Candlewood Lake watershed has changed dramatically over the course of the lake's life, becoming more urbanized and losing forested and agricultural lands. Since 1970, the percentage of the watershed classified as urban has increased from 11.7% to 28.3% in 2007 (Table 2) (Kohli et al. 2017).

Year	Urban (%)	Agriculture (%)	Wooded (%)	Water (%)
1970	11.7	8.5	57.0	22.0
1977	19.5	2.1	57.0	22.2
1990	28.7	5.6	43.6	21.7
2007	28.3	1.9	47.1	22.7

Table 2*: Candlewood Lake Watershed percent coverage of different land classifications (Table from Kohli et al. 2017).*

The Candlewood Lake Monitoring Program

Long-term management of water resources requires consistent and standardized monitoring to make informed management decisions. By tracking critical water chemistry and biological metrics that are indicators of lake health, we can analyze how management activities are affecting the in-lake ecosystem, and what additional management activities may be necessary. To that end, the CLA began a monitoring program in 1983 to provide a scientifically standardized method of assessing Candlewood Lake & Squantz Ponds health and water quality over time to the surrounding communities.

Initially undertaken by researchers from Western Connecticut State University (WCSU) and later by Connecticut College (CC), the CLA has conducted this monitoring itself since 1998, with the exception of the years 2017-2019, when the monitoring was contracted to Aquatic Ecosystems Research (AER), a freshwater consulting organization specializing in in-lake chemical monitoring. Since 1999, all whole-water sample laboratory analyses have been performed at Hydro Technologies, Inc. at their CT Department of Health certified laboratory in New Milford, CT.

2021 is the first year where every month from May-October there were two distinct sampling events (one early month, and one late month sampling). This was done to give the CLA a more fine-grained view of the chemical monitoring results, allowing us to better understand trends over the course of a season, as well as being able to calculate representative averages of our key metrics more accurately. We hope to continue with this twice monthly schedule moving forward. For the sake of keeping this report a reasonable size, raw data has not been included as an appendix, but all raw data and lab results are available from the Candlewood Lake Authority upon request: science@candlewoodlakeauthority.org

Materials & Methods

The CLA began its water quality monitoring program in 1983 to provide the community with a scientifically rigorous and standardized method of assessing changes in Candlewood Lake and Squantz Pond over time. The program has continued largely uninterrupted since then, providing us with historical data for 38 years and counting.

More Specifically, The Candlewood Lake Authority has been conducting monthly monitoring from May – October of 4 sites on Candlewood Lake, and one Site on Squantz Pond. From 1985-1987 sites in Lattins Cove, Pocono Point, and the southern end of the New Milford arm of the lake were sampled as well. From 1985-1990 an additional site in New Fairfield Bay was sampled. From 1988-1990 the New Fairfield Bay site was sampled instead of the standard New Fairfield site. In 1990 the New Fairfield site was re-established, and the New Fairfield Bay site was eliminated.

The monitoring has taken some different forms over the years, and different metrics have been added, eliminated, and transferred to new methods of measurement at various times over the course of the monitoring's history. However, the metrics being measured regularly at each monitoring location are:

At each location:

1. Secchi Depth (m)

At 1-meter intervals:

2. Depth (m)
3. Temperature (C°)
4. Dissolved Oxygen (mg/l)
5. pH
6. Standard Conductivity (μmhos/cm)
7. Relative Cyanobacteria (cells/mL)
8. Relative Chlorophyll-a (μg/L) - Started in 2019

At the Epi, Meta, and Hypolimnion:

9. Total Phosphorous (ppb)
10. Total Nitrogen (ppm)
11. Chlorophyll-a ($\mu g/m^3$)
12. Ca^{++} (mg/l) – Bi-monthly
13. Mg^{++} (mg/l) – Bi-monthly
14. Na^{+} (mg/l) – Bi-monthly
15. K^{+} (mg/l) – Bi-monthly
16. Cl^{-} (mg/L) –Bi-monthly

Phaeophytin, phytoplankton diversity and cell counts (including Cyanobacteria cell counts), and Chlorophyll b and c have also been included in past years' monitoring, but have been monitored inconsistently, or monitoring has ceased. Phytoplankton diversity and cell counts were monitored from 1985-1998, at which point that monitoring was discontinued until 2017, and has been re-incorporated into the monitoring from 2017 to 2020. Phytoplankton monitoring was not included in the 2021 monitoring and will be re-incorporated on a 3-year rotating basis. In 2011, a Zebra Mussel Veliger Monitoring program was added in conjunction to the normal monthly monitoring and has continued since.

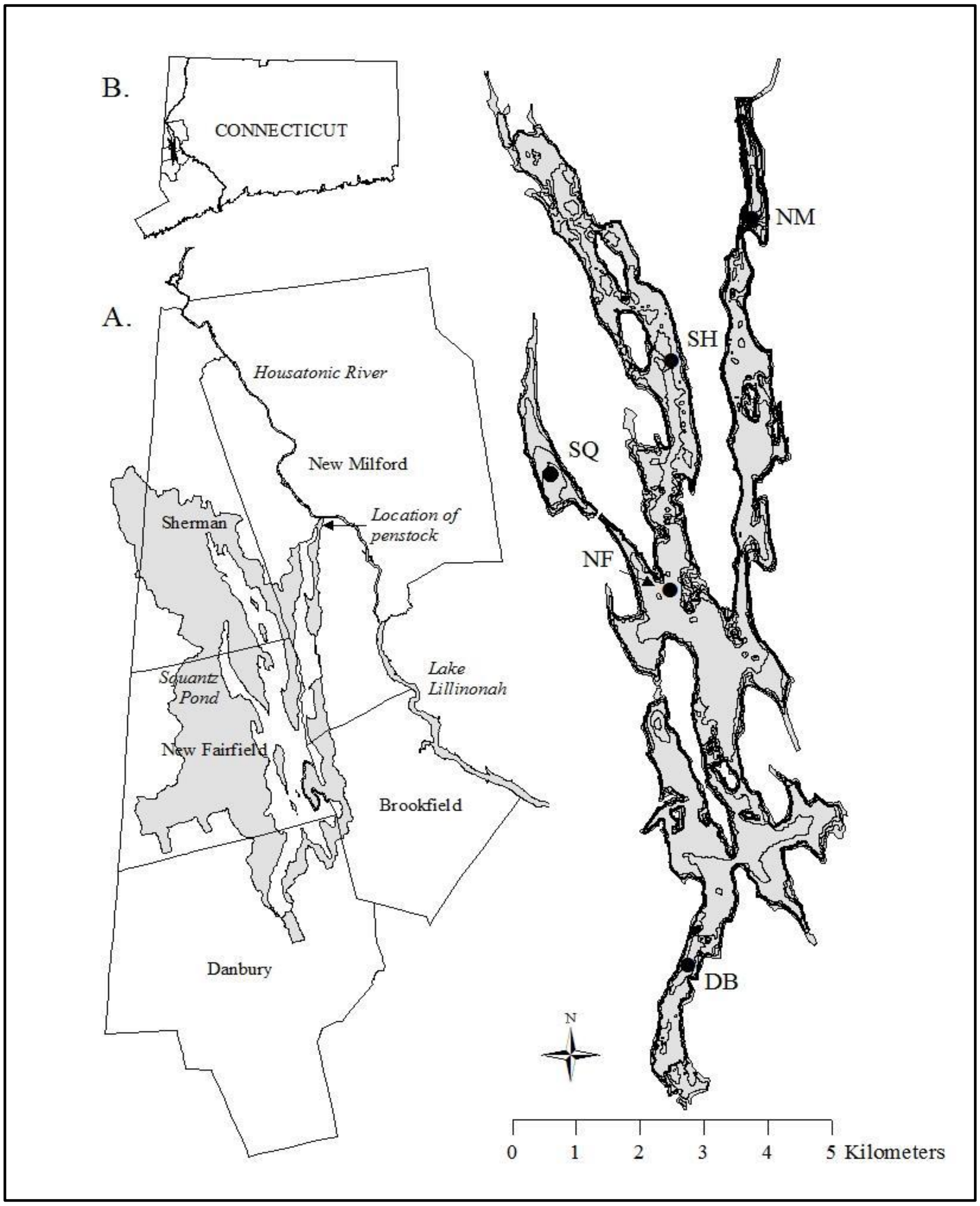


Figure 1: *A) Relation of the Candlewood Lake Watershed to the five bordering municipalities. B) Location of watershed and municipalities in the state of Connecticut. C) Location of the five sampling sites on Candlewood Lake and Squantz Pond.*

Results

Temperature and Dissolved Oxygen Profiles

Candlewood Lake is a dimictic lake, meaning that twice per year, the temperature difference between the surface water and the lake bottom is negligible. That proves true once again, as our analysis bears out that in the beginning of the season (May) and end of the season (October) the water column is largely homogenous.

	Danbury		New Fairfield		New Milford		Sherman		Squantz	
	Metalim. Boundary (m)	Anoxic Layer (m)	Metalim. Boundary (m)	Anoxic Layer (m)	Metalim. Boundary (m)	Anoxic Layer (m)	Metalim. Boundary (m)	Anoxic Layer (m)	Metalim. Boundary (m)	Anoxic Layer (m)
11-May	N/A	N/A	N/A	N/A	7-11	N/A	N/A	N/A	6-9	N/A
25-May	4-6	N/A	5-8	N/A	7-9	N/A	6-7	N/A	4-8	N/A
10-Jun	4-7	11	5-8	N/A	8-12	N/A	2-5	N/A	4-9	N/A
24-Jun	6-8	9	5-8	9	5-9	22	5-8	10	4-9	10
8-Jul	5-8	7	6-9	9	4-8	22	5-8	8	5-9	8
27-Jul	6-9	7	5-9	7	5-9	8-13/19	5-9	8	5-9	8
11-Aug	6-9	7	7-10	8	6-10	8-14/21	5-9	8	6-10	7
26-Aug	6-9	7	7-10	8	6-10	8-15/18	6-9	8	6-10	8
8-Sep	7-9	8	7-9	9	7-11	9	8-10	9	8-11	9
27-Sep	8-10	10	8-11	9	8-12	9	8-10	10	8-12	9
6-Oct	10-11	11	9-11	11	9-14	12	9-11	10	9-12	11
28-Oct	N/A	N/A	6-10	N/A	13-17	15	N/A	N/A	10-13	11

Table 3: *Stratification, mixing, and oxygen depletion characteristics at 4 locations on Candlewood Lake, and one location on Squantz Pond in 2021. The metalimnetic boundaries are presented as meters below the surface, and the anoxic layer is presented as the upper boundary of the anoxic zone, extending from that level to the bottom.*

The tendencies of Candlewood Lake of top-to-bottom mixing, and strong mid-season stratification followed by a period of mixing are characteristic of deep lakes in the American northeast. The colder, denser, water "sinks" to the bottom of the water column, effectively preventing mixing with the shallower surface water – creating the anoxic layer in the lake bottom. These layers are shown in Figure 1. As surface waters begin to cool at the end of the season, the metalimnion (middle layer) recedes deeper into the water column until

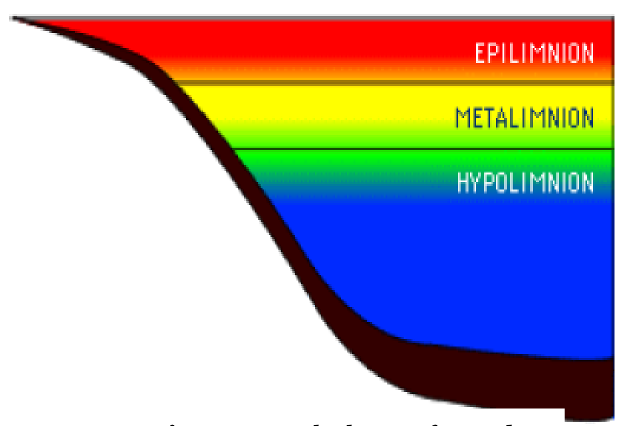


Figure 2: *Lake layers formed during stratification of the water column. (Source: UMN)*

such time that the temperature of the column reaches a homogenous state, and the anoxic zone disappears, allowing for a consistent level of dissolved oxygen throughout the water column.

When we began our monitoring in May Danbury, New Fairfield, and Sherman were well mixed, meaning the water column was mostly homogenous in regard to dissolved oxygen (DO) – although in the bottom 2 meters of both, a drop in DO was beginning. This is due to respirating single-celled organisms utilizing that oxygen to digest sinking phytoplankton and other materials for energy. A thermocline (the "barrier" of the largest temperature difference between the epilimnion and the hypolimnion, preventing mixing) was beginning to form in New Milford, the deepest sample site, and Squantz Pond in early May. Relatively strong stratification began in late May at all 5 sites, peaking in July. Anoxic zones weren't apparent until mid to late June. Temperature and oxygen profiles generally mirror one another due to their strong relationship with thermal resistance to mixing and lake stratification.

The New Milford site shows a unique property of two separate anoxic zones. With low levels of dissolved oxygen between the two zones. This is our deepest site, but the cause of this is somewhat unclear. It could indicate outgassing at a certain point in the deep lake's geology or indicate layers of oxygen utilization by deep water respirating bacteria.

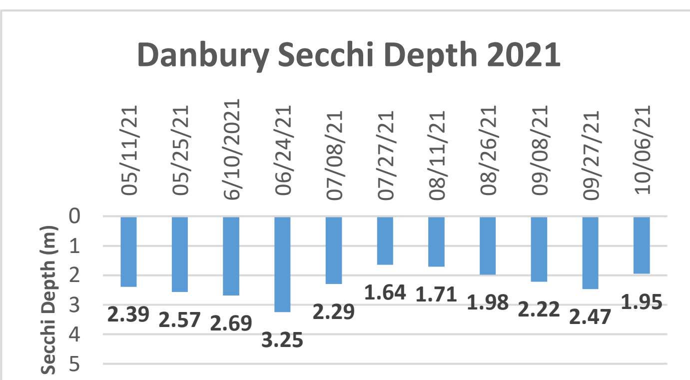
Anoxic zones in the hypolimnion require respirating bacteria to use anaerobic respiration, increasing nutrient release in the hypolimnion as compounds containing both nitrogen and phosphorus are broken down into forms usable by bacteria. This is known as "internal loading" and is a critical component of lake monitoring and management. Mixing allows for the hypolimnion to be refreshed with oxygen, allowing for aerobic respiration and a relative pause in nutrient release while the water column is homogenous. As temperatures continue to increase due to climate change, strong stratification can last for a longer period, increasing the potential for nutrient release in anoxic zones. This can and will accelerate eutrophication (lake "aging") in the long term.

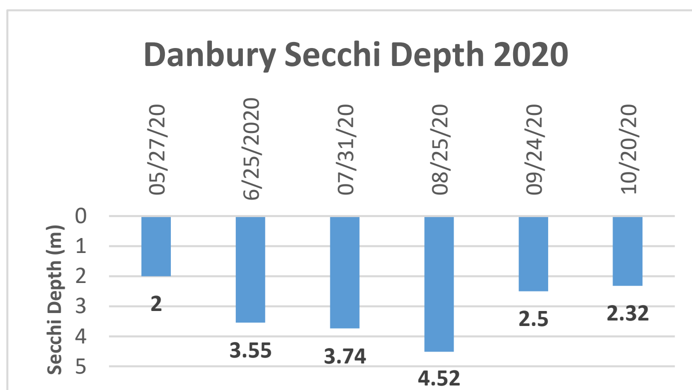
Secchi Transparency

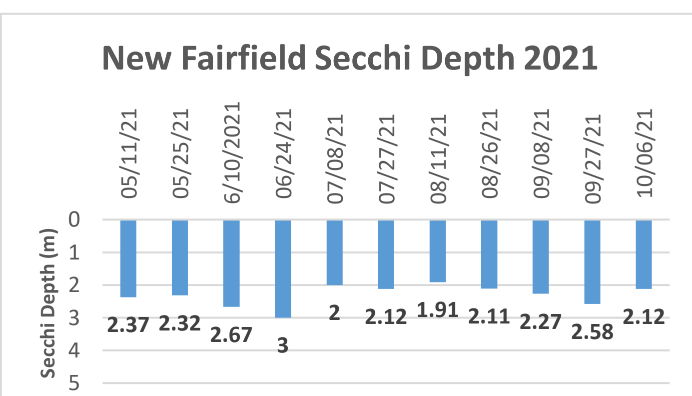
In 2021 secchi transparency (water clarity) in Candlewood Lake ranged from a low of 1.64m in Danbury in late July (although the lowest reading for this year's monitoring was 1.4m in Squantz Pond) to a high of 3.25m in both Danbury and New Milford in late June. The average reading across the whole of both Candlewood and Squantz was 2.38m, with the highest average being New Milford at 2.59m, and the lowest being Sherman at 2.27m.

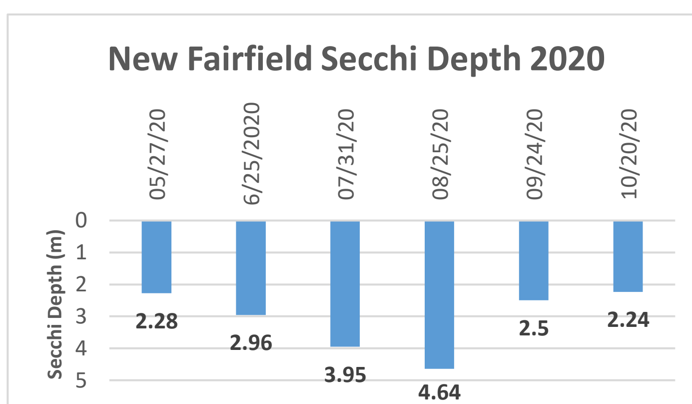
	DB Secchi (m)	NF Secchi (m)	NM Secchi (m)	SH Secchi (m)	SQ Secchi (m)	Average
05/11/21	2.39	2.37	3	2.11	2.54	2.48
05/25/21	2.57	2.32	2.34	2.47	3.03	2.55
6/10/2021	2.69	2.67	2.7	2.87	3.15	2.82
06/24/21	3.25	3	3.25	2.72	2.5	2.94
07/08/21	2.29	2	2.15	2.12	2.35	2.18
07/27/21	1.64	2.12	2.26	2.19	2.50	2.14
08/11/21	1.71	1.91	1.87	1.91	2.78	2.04
08/26/21	1.98	2.11	2.10	2.06	2.18	2.09
09/08/21	2.22	2.27	2.54	2.04	2.29	2.27
09/27/21	2.47	2.58	3.00	2.35	1.92	2.46
10/06/21	1.95	2.12	3.24	2.1	1.4	2.16
Average	2.29	2.32	2.59	2.27	2.42	**2.38**

Table 4: *Secchi depths measured at each sampling location during the 2021 season.*









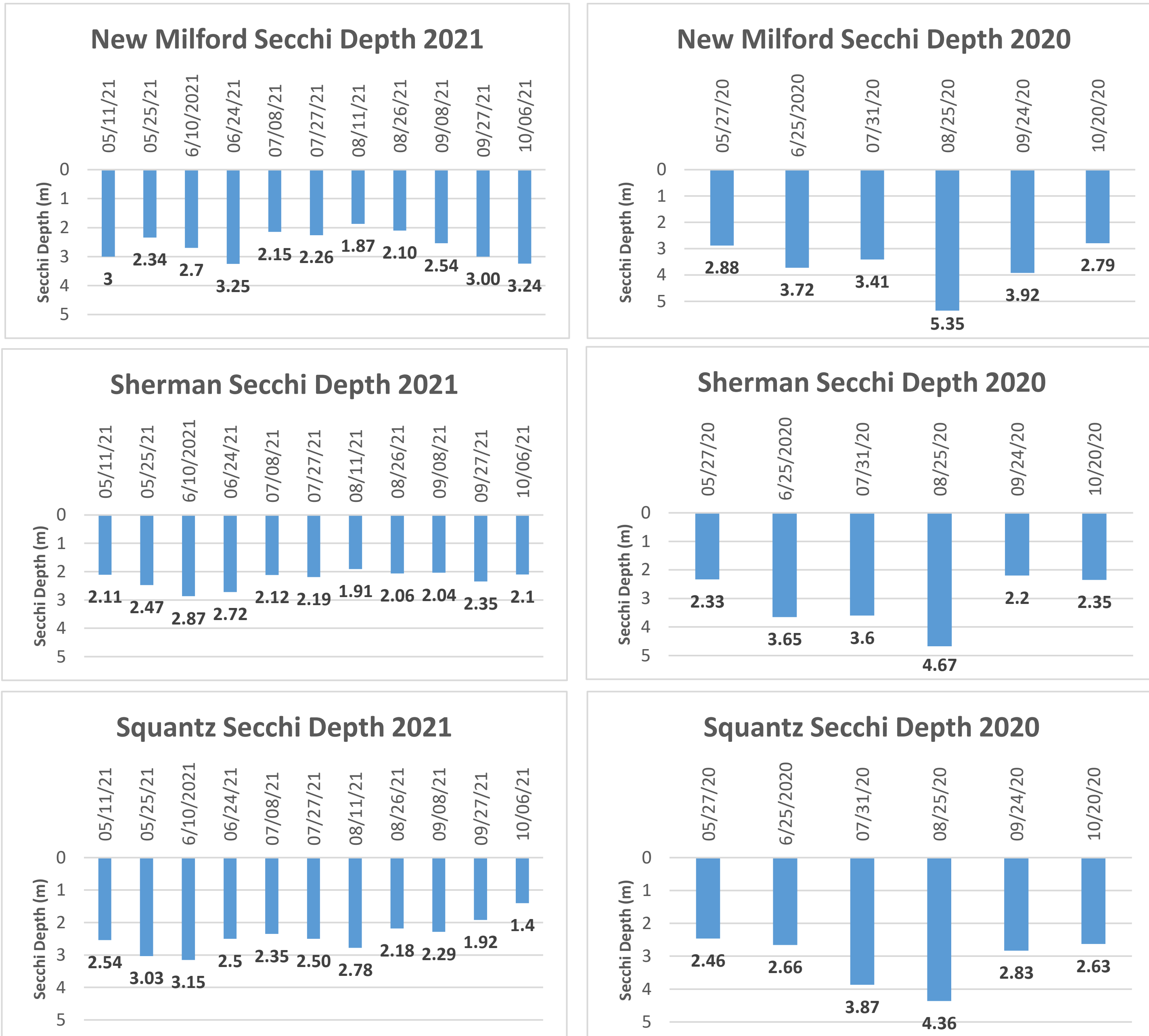


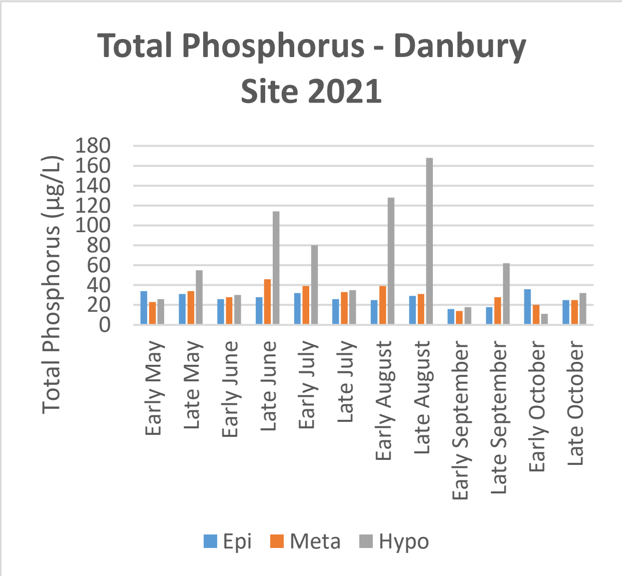
Figure 3: *Measured Secchi Transparency in Candlewood and Squantz in 2021 & 2020.*

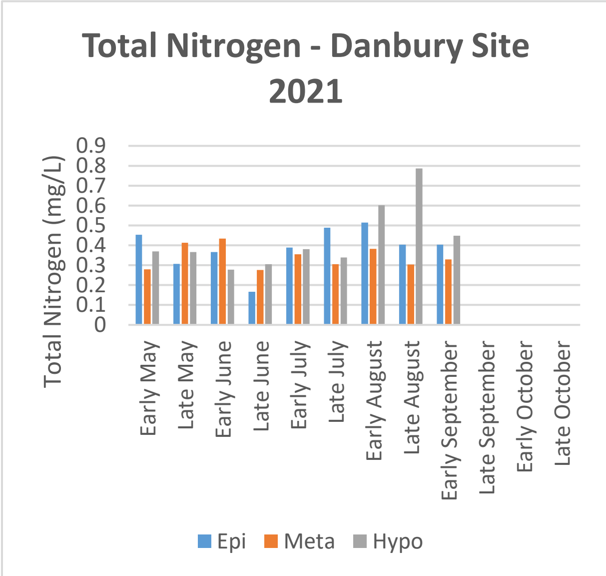
Compared to 2020, secchi transparency has decreased on average. The average in 2020 was 3.23, which was the second highest average in the history of monitoring (only 1989 was higher at 3.38). In 2021 we added one additional sampling per month, which can help us pinpoint the true average measurement, but water clarity was noticeably lower this season, due in part to higher average chl-a values, as well as higher blue-green algae cell counts, which can likely be attributed to more large storm events during the 2021 boating season (as measured at the Danbury Weather Station).

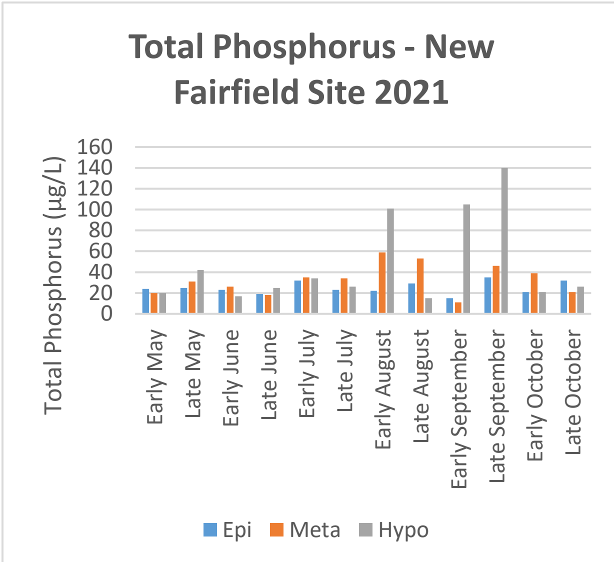
Nutrient Levels

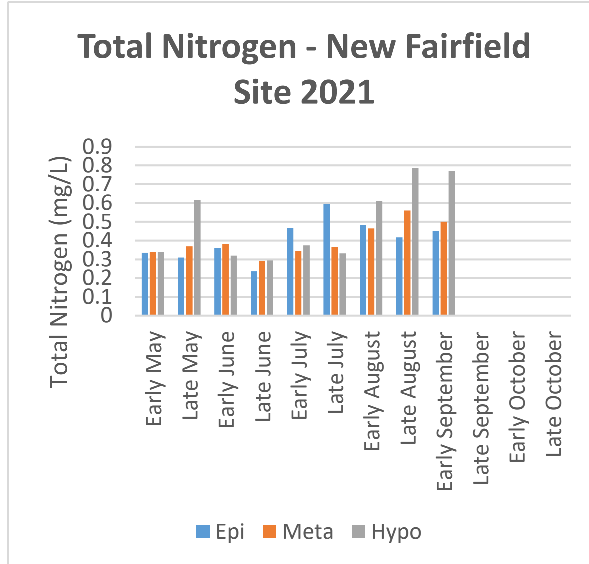
In 2021, nutrient measurements were taken 36 times at each site. This includes 3 samples at each location (Epilimnion, Metalimnion, and Hypolimnion samples) twice per month, which is twice as many samples as taken in the past. The hope with more regular sampling throughout the season is that it will give us a better impression of nutrient dynamics in the water, and how that might impact blue-green and green algae growth in the water. This will also allow for a closer look at how nutrients are "locked" into the hypolimnion due to stratification and subsequent internal loading, and when those nutrients begin to mix with the rest of the water column. We sample for total phosphorus, as well as four different forms of Nitrogen, but to visualize the nitrogen levels, we will use total nitrogen levels.

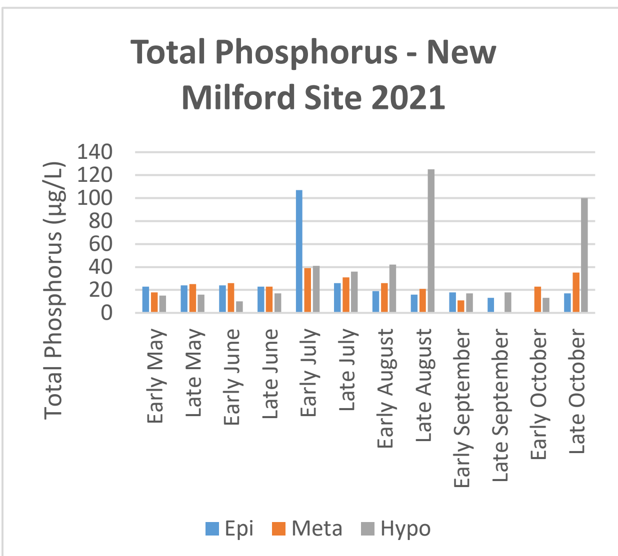
One important caveat for the 2021 monitoring year is that our analysis lab changed their testing methodology for Kjeldahl Nitrogen (TKN) starting in September. Candlewood Lake generally has TKN readings anywhere between .2 to 1.0 mg/L, and TKN represents the lion's share of total nitrogen measurements in Candlewood. Unfortunately, this new technique calibrates the readings so that any reading of TKN below 1 mg/L is reported as "non-detected." That means, for the months of September and October, most readings are reported as "non detected", but are likely comparable to other months' measurements. We will work with our lab or pursue different analytical solutions to remedy this for the 2022 season. There is still a lot of useful information in the months from May-Early September, and this switch only impacted nitrogen measurements, and did not impact any of our other metrics.

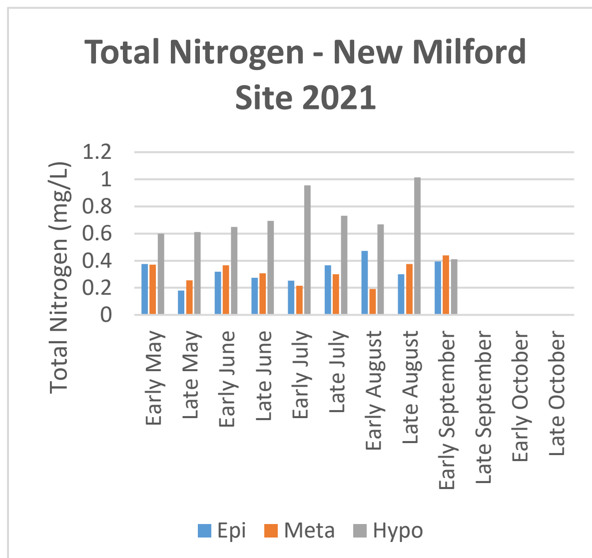


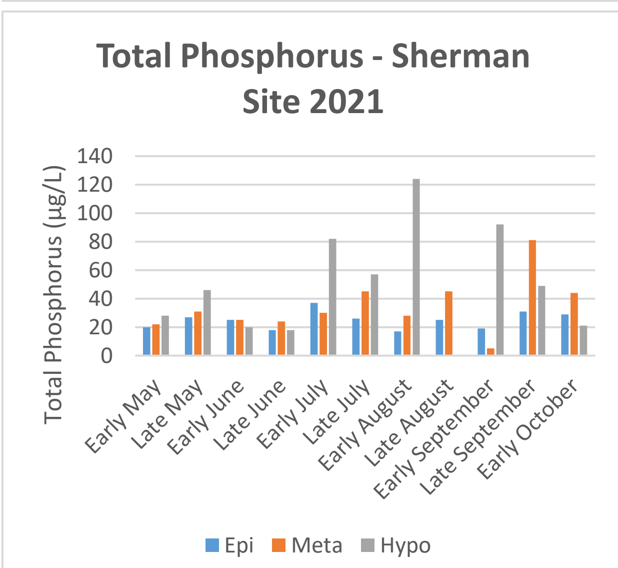


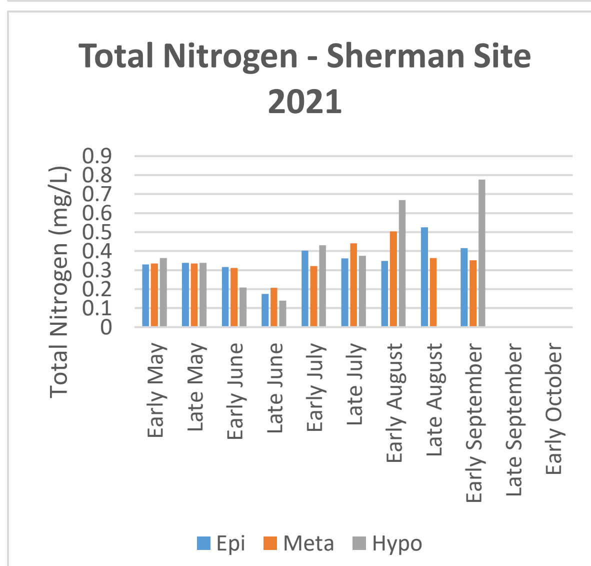

Total Phosphorus - New Fairfield Site 2021
Total Phosphorus (µg/L)
160
140
120
100
80
60
40
20
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Late October
Epi
Meta
Hypo

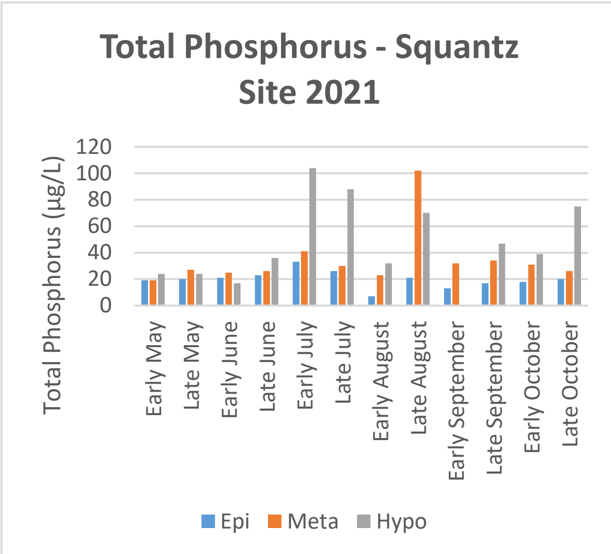

Total Nitrogen - New Fairfield Site 2021
Total Nitrogen (mg/L)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Late October
Epi
Meta
Hypo


Total Phosphorus - New Milford Site 2021
Total Phosphorus (µg/L)
140
120
100
80
60
40
20
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Late October
Epi
Meta
Hypo


Total Nitrogen - New Milford Site 2021
Total Nitrogen (mg/L)
1.2
1
0.8
0.6
0.4
0.2
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Late October
Epi
Meta
Hypo


Total Phosphorus - Sherman Site 2021
Total Phosphorus (µg/L)
140
120
100
80
60
40
20
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Epi
Meta
Hypo


Total Nitrogen - Sherman Site 2021
Total Nitrogen (mg/L)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Early May
Late May
Early June
Late June
Early July
Late July
Early August
Late August
Early September
Late September
Early October
Epi
Meta
Hypo



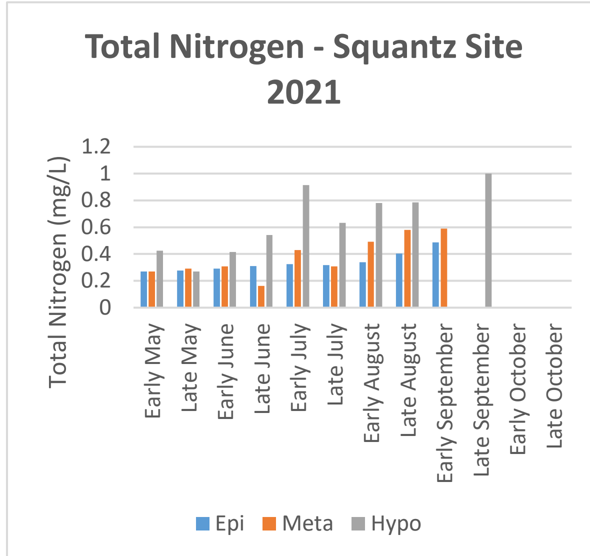


Figure 4: *Measured Total Phosphorus and Nitrogen at 3 depths in 2021. Note that late September through late October Total Nitrogen measurements are inaccurate due to a change in lab methodology, and there is no late October nutrient sampling at the Sherman site.*

While there are different schools of thought about which of these two nutrients are more important in algae dynamics and eutrophication in freshwater systems, both are critical raw materials for algae blooms. Historically, Candlewood Lake has been considered phosphorus limited, and the blue-green algae community has been largely dominated by Microcystis cyanobacteria. To examine how the nutrient profile in Candlewood has changed over the course of the CLA's monitoring, it is useful to visualize epilimnion phosphorus levels, as those are the most relevant to Candlewood Lake's ecosystem, and thus the most likely to impact recreation during the boating season.

In 2021, the largest measurements for both nitrogen and phosphorus were found in the hypolimnion in July and August. This is indicative of internal loading in hypoxic conditions, a well-documented phenomenon in Candlewood Lake. Sediments at the lake bottom contribute nutrients to the system during the midsummer months, and those nutrients are incorporated into the rest of the water column after mixing.

One unusual reading of 107 µg/L of Phosphorus in the epilimnion of New Milford is a clear outlier in the data and could be due to sampling or lab error. In fact, if we take the interquartile range for the New Milford Phosphorus readings (IQR = 11.8) and multiply it by 3 and add it to the third quartile (Q_3 = 25.8), we get the limit for a strong outlier of 61.2, which this measurement is substantially higher than. We will be diligent in looking at this site to see if this outlier measurement repeats itself.

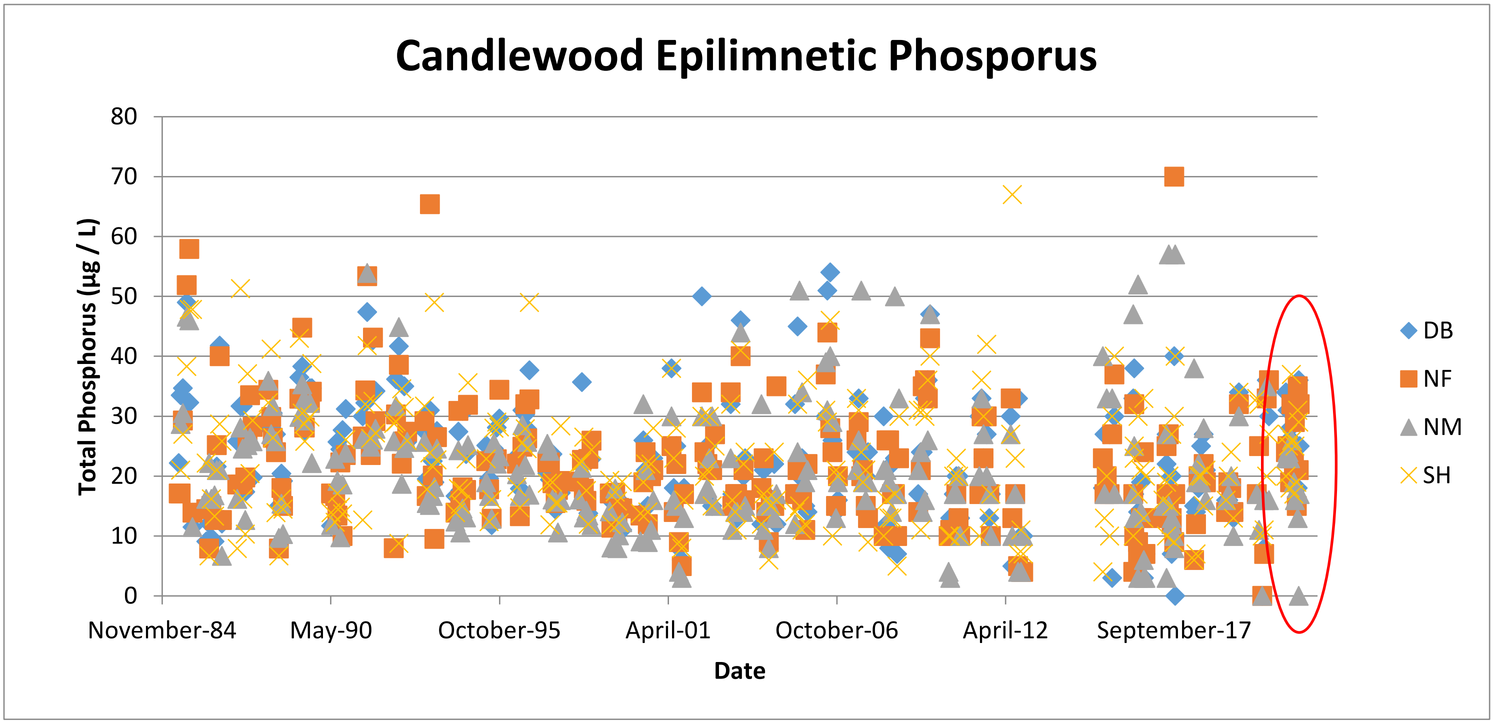


Figure 5: *Epilimnion phosphorus measurements at all 4 Candlewood monitoring sites taken from 1985 to 2021. The 2021 measurements have been highlighted.*

To help illustrate the trend over time of these measurements, we can look specifically at one sampling location, in this case we will look at Danbury:

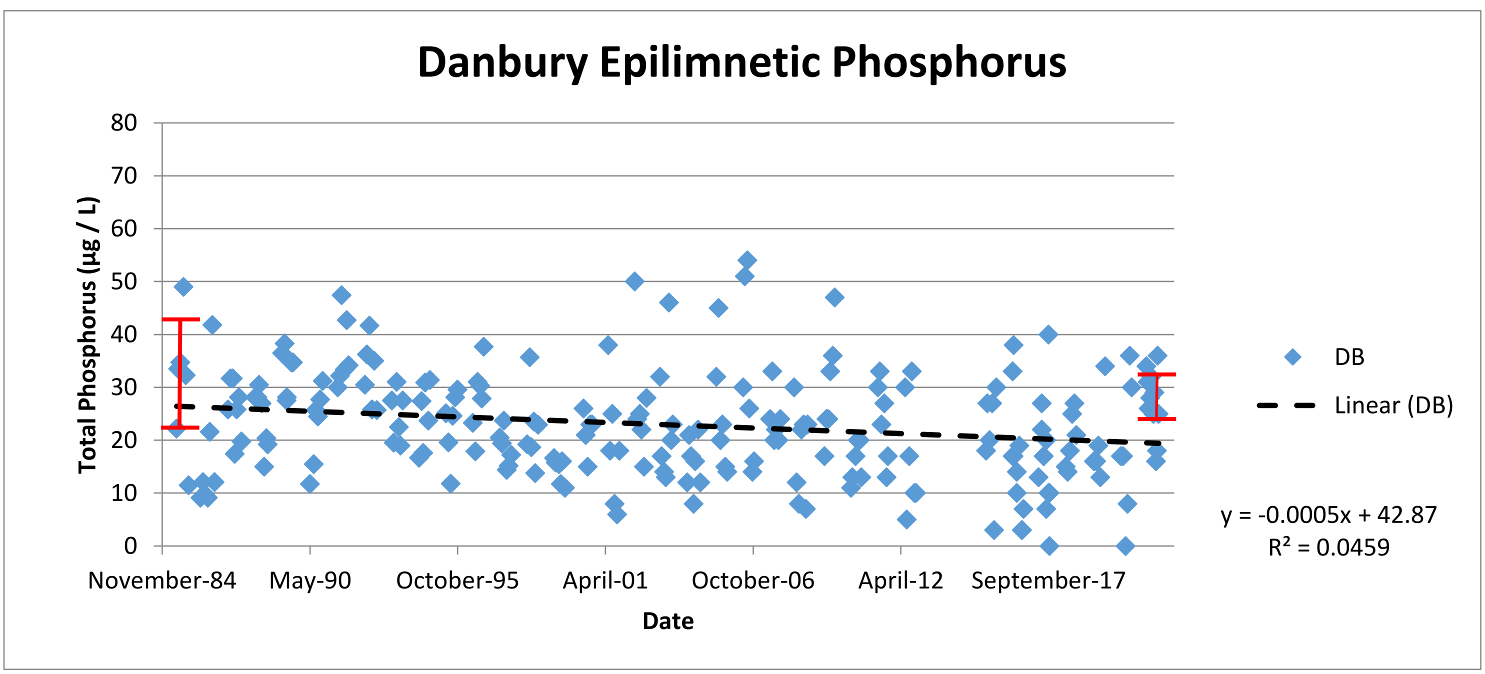


Figure 6: *Danbury Epilimnion Phosphorus from 1985-2021*. 95% confidence intervals for 1985 and 2021 are highlighted

While there is substantial variation in the data, (R^2 value of 0.0459) the negative slope of the line is encouraging. To help illustrate the change, 95% confidence intervals for the mean have been calculated for 1985 and 2021. The Danbury Epiliniotic phosphorus level 95% confidence interval in 2021 is *23.839-30.561* while the 1985 confidence interval is *20.338-40.662*. The addition of twice monthly sampling in 2021 has allowed us to tighten the interval, but unfortunately there is complete overlap between the intervals, meaning that no conclusive significance can be determined. However, the trend and smaller upper-bound are encouraging, and hopefully continued expanded sampling can can help us determine a more accurate mean measurement moving forward.

New Milford is the only site with a positive trend for epilimnion phosphporus over time, but the slope of that line is currently $5x10^{-5}$ or 0.00005. The slope for New Fairfield is -0.0004, and in Sherman it is -0.0003, all three other sites with substantially stronger negative slopes than New Milford's positive slope. Nonetheless, we will continue to pay careful attention to New Milford epilimnetic phosphorus measurements, as there might be other factors including the proximity of the site to the Housatonic River penstock that might be impacting these results. Also of note is the strong outlier reading of 107 µg/L of phosphorus in the epilimnion of New Milford this year, which might be skewing these results. If removed, the slope for New Milford becomes -0.0001, putting it more in line with the other sites.

Chlorophyll Concentrations

Chl-a	Early May	Late May	Early June	Late June	Early July	Late July	Early August	Late August	Early September	Late September	Early October	Late October	Average
DB	9.46	3.7	3.87	3.62	8.17	11.69	8.39	8.93	11.57	6.75	19.45	8.69	**8.69**
NF	9.09	1.93	4.03	3.01	5.36	9.57	7.02	9.1	12.66	7.37	18.77	8.45	**8.03**
NM	15.41	2.84	3.02	4.14	7.42	8.4	7.09	7.28	9.56	3.71	7.6	4.56	**6.75**
SH	11.23	2.62	4.08	6.74	6.82	12.33	9.91	8.33	11.32	11.87	17.78	n/a	**9.37**
SQ	6.74	2.09	2.66	9.73	4.64	5.96	4.12	8.63	12.26	14.76	23.8	18.15	**9.46**
Average	**10.39**	**2.64**	**3.53**	**5.45**	**6.48**	**9.59**	**7.31**	**8.45**	**11.47**	**8.89**	**17.48**	**9.96**	**8.46**

Table 4: Chorophyll-a as measured in the lab during the 2021 season (µg/L). Note that there was no chl-a sample for late october in Sherman.

One of the best ways to measure both eutrophication and potential recreational impact on a freshwater lake system is by measuring Chlorophyll-a. This measurement is effectively a measurement of the algal material in the lake by measuring the green pigment present in green algae and cyanobacteria. The largest measurement taken in 2021 was in Squantz Pond in early October at 23.8 µg/L, which probably explains why Squantz had the highest mean chlorophyll-a concentrations, despite having a higher average clarity than most sites on Candlewood Lake. The highest measurement in Candlewood was in the same sampling batch in Danbury at 19.45 µg/L. These high numbers in Early october (indeed, it had by far the highest average measurement of all the sampling events this year) is a good indication of when substantial lake mixing began to take place. The hypolimnion was getting loaded with nutrients throughout the season when the lake was stratified, which then mixed with the epilimnion in late spetember and early October, fueling algae growth. This is also borne out in the nutrient data, where we see phosphours levels in the hypolimnion drop off at the end of the season. The reason we don't see a spike in the epilimnion is because those nutrients are being used by the algae community, so we see those affects here in the chl-a results.

By plotting chlorophyll-against secchi depth, we can get a good idea of how the lake generally compares to other years. This is a useful way to track two critical measures of eutrophication, while also displaying important aspects of the recreational value of the lake compared to past years.

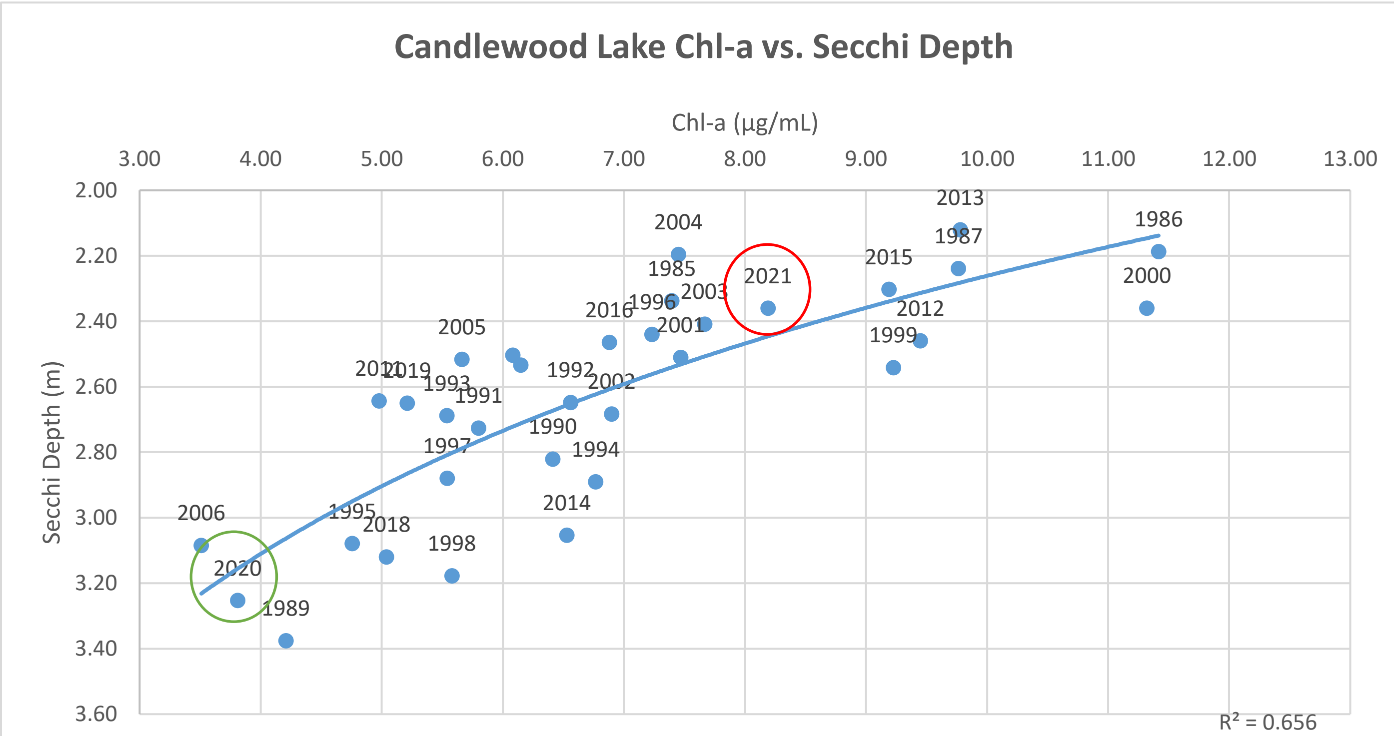


Figure 7: Chlorophyll-a plotted against Secchi Depth in Candlewood from 1985-2021. The years 2021 and 2020 have been highlighted.

The above figure is really useful in displaying the general productivity (that is, algae growth) of the lake, and comparing different years. The line shows the general (logarithmic) relationship between the two metrics. 2021 is a year where we saw higher than average chl-a measurements, and lower than average clarity measurements. While there are clearly years where chl-a has been higher (greener water) and secchi depth has been lower (lower clarity), 2021 is on the high end of the lower spectrum when it comes to these measurements. 2020 on the other hand, was a near record setting year, with the second highest average clarity, and the second lowest average chl-a. This banner year was likely due to a host of factors, including very low precipitation and low mixing, denuding the epilimnion of most of its usable nutrients for algae early in the season. 2021, marked by higher precipitation measurements allowed more runoff and non-point nutrient input into the lake, ultimately explaining its lower measurements. While there is no clear trend to this relationship over time, the graph presents a useful method to comparing the "recreational usability" of the lake between years.

In 2019 we added a new sensor to our probe to measure chlorophyll-a using spectrophotometry. This uses a specific wavelength of light that bounces off of chlorophyll-a pigment to measure the concentration in the water and returning a relative value based on that measurement and the water volume in the sensor, rather than taking an entire water sample, filtering it, and measuring the pigment in the lab. We purchased this sensor in the hopes that a relationship could be established between the two methods that would allow us to rely on the new sensor rather than having to take whole water samples to the lab for analysis. To help establish that relationship, we have to compare the results from the two methods and see what their linear relationship looks like. We can then run an F-test to see if that relationship is indeed significant, and we can look at the R^2 value to see how strong that relationshisp is (how much the difference in the two measurements can be explained by only those two measurements).

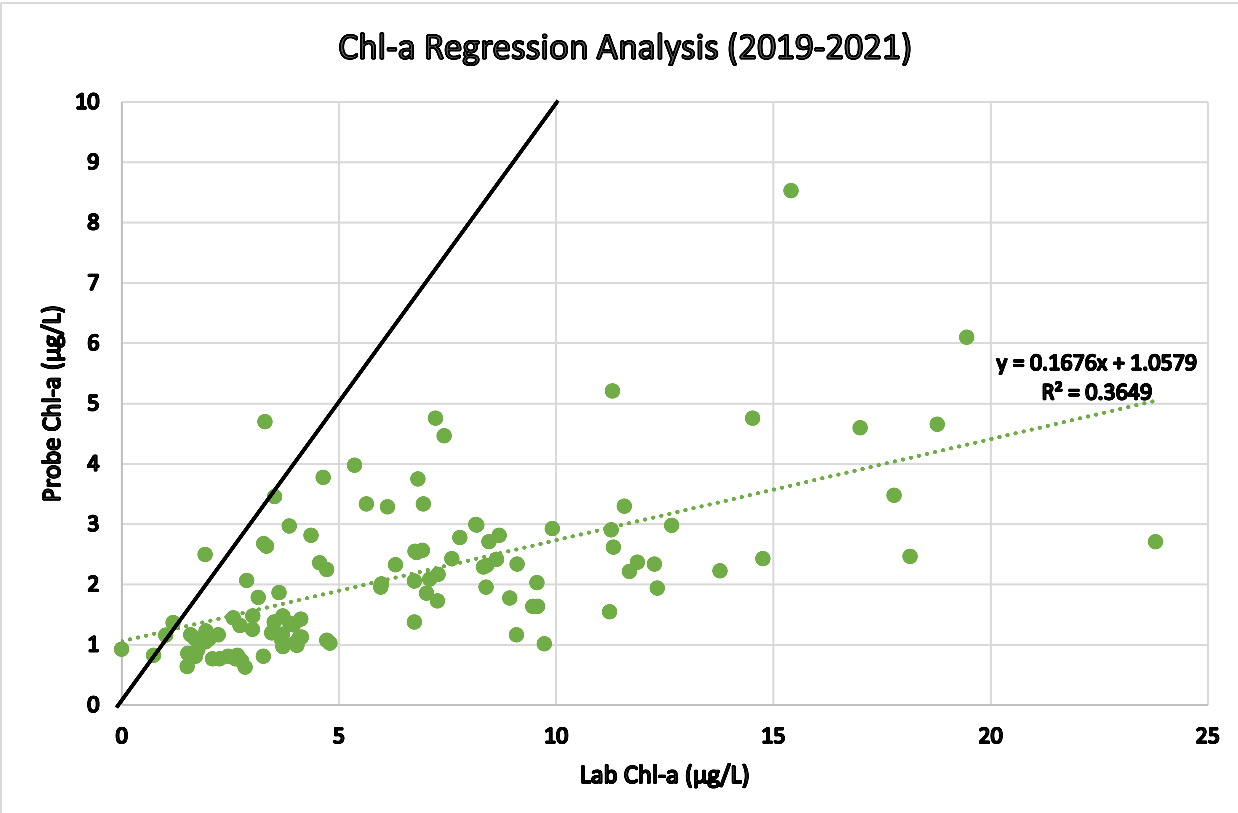


Figure 8: Regression model for Probe and Lab measurements of Chl-a at 1m depth, including the equation for the relationship and the R^2 value. The black line illustrates what a 1:1 relationship would look like for the measurements.

This green line shows the relationship between the probe measurements (the dependent variable, in this case) and the lab measurements (the independent variable). The black line shows the ideal 1:1 relationship that would occur if the probe was measuring exactly the same amount of chl-a as the lab was. Instead, we see that generally the probe measures the amount of chl-a as less than what we find in the lab (the only exceptions are thos measurements above the black line). This makes sense logically, as the sensor on our probe is more limited to chance, if a high level of algae or cyanobacteria happens to be passing through the sensor at the time of meaurement or not, while the lab measurements take a much larger volume of water and measure the entire concentration in that sample. This makes the lab samples more representative of the ”population” of 1m depth where the samples are taken than the sensor samples. This is why we also see that the goodness of fit of the trendline gets worse as the concentration increases, as the likelihood that the sensor might be missing areas of high algae concentration increases as the total amount of algal material in the 1m band increases.

With all that said, the F-test of significance returns a p-value (that is, the test of whether the relationship between the variables is significant at all) of 1.41×10^{-12}. The closer this number is to 0, the more certain we can be that we can reject the null hypothesis that there is effectively no relationship between the two measurements. What this means is that while the entire relationship between these measurements its confounded by other things (like the concentration issue mentioned above), that there is very strong evidence to say that these two variables are related in at least some capacity. The R^2 value can tell us, in general, how much of that relationship can be attributed to these two variables, and in this case, 36.5% of the relationship can be explained through comparison of these two variables alone. Ultimately, the trend does not fit the data well enough for me to confidently say we can switch to using the new sensor entirely (by correcting the values with the equation $y=0.1676x+1.0579$). So we will continue using both methods, and analyzing the differences in the hopes that we can strengthen the relationship with more data in the future.

Conductivity

Conductivity is a measurement of how well the water can conduct an electric charge. This is a good analog for measuring the level of dissolved salts in the water, as these salts dissolve into charged ions, which increase the water's ability to conduct an electric charge. This means that the higher the conductivity is, the higher the "saltiness" of the water. Over time, Candlewood has been accumulating more and more of these ions mostly through stormwater runoff and stormwater discharges that empty into the lake, precipitating a pretty clear increase in the water's conductivity.

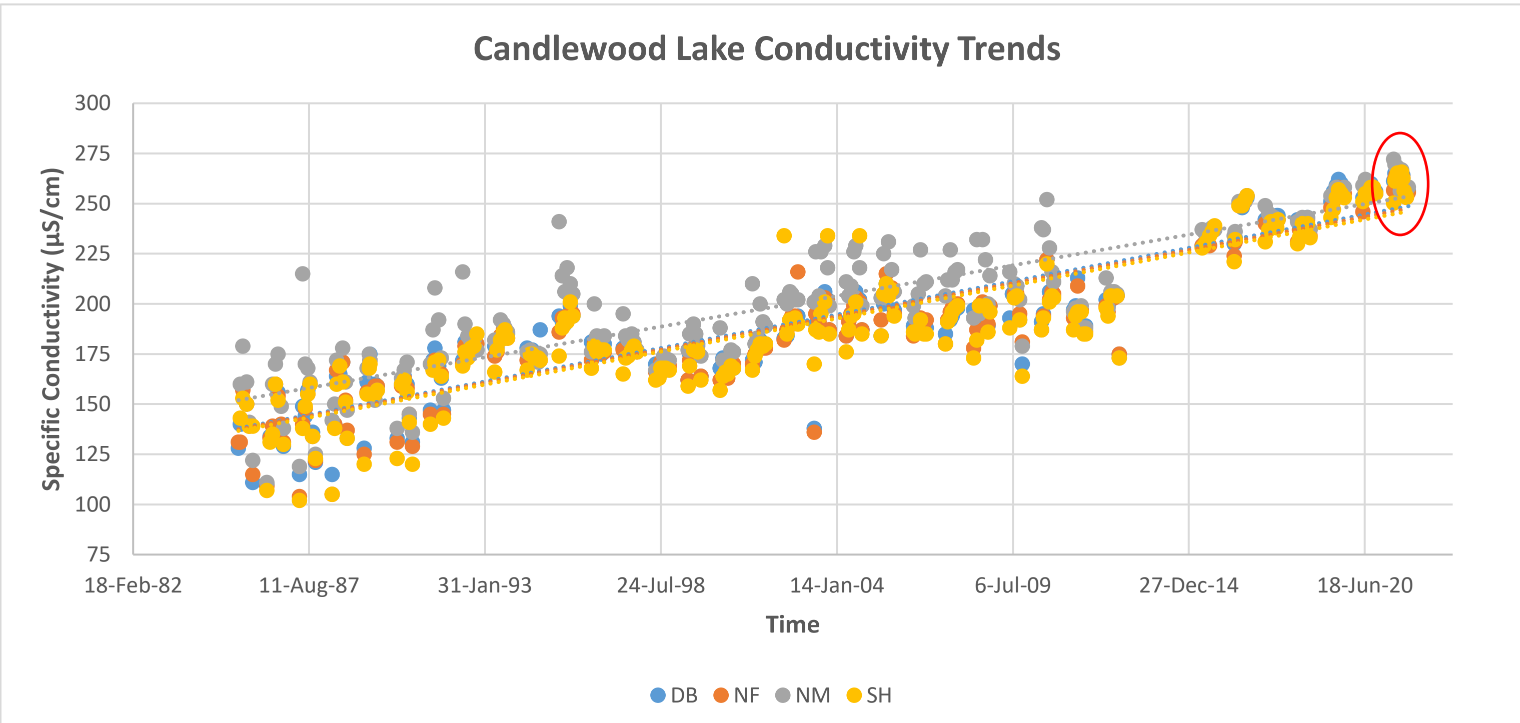


Figure 9: Candlewood Lake Conductivity from 1985-2021 measured at 1m depth. 2021 has been highlighted, and trend lines have been included to illustrate the clear increase over time.

This concerning trend continued in 2021, increasing from an average of 256 in 2020 to an average of 261 in 2021. To put these numbers in context, seawater has a conductivity of 50,000 µS/cm, and the limit of drinkable freshwater is around 3000 µS/cm, so while the lake is not in immenent danger of becoming a salt lake, there are species of fish and plankton that are more sensitive to these measurements, and eventually, should the trend of salt accumulation in the lake continue, we might begin to have impacts on the lake's fishery and ecosystem.

Cations and Anions

As part of the measurement of salts in Candlewood Lake, bi-monthly we test the water for key positive and negatively charged ions that are key parts of certiain biological or ecological pathways. Those ions are calcium, magnesium, sodium, potassium, and chlorine. The measurement of these ions began in 1992 and has continued since

	Sodium (Na+)	Calcium (Ca++)	Chloride (Cl-)	Magnesium (Mg++)
Danbury	18.3	21.0	31.3	7.5
New Fairfield	17.0	21.3	30.7	7.5
New Milford	17.7	21.7	30.7	7.7
Sherman	17.0	21.0	30.3	7.5
Squantz	13.0	12.7	23.3	4.8

Table 5: 2021 average cation and anion concentrations measured at 1m depth (in mg/L). Note that potassium was also measured, but never reached detectable levels in collected samples.

Of particular interest are the calcium ion levels, as these are a critical raw material for zebra mussel shell formation, and there are well documented thresholds for effective zebra mussel infestation of waterbodies based on calcium levels.

Risk	pH	Calcium (mg/L)
Low	<7.4	<12.0
Medium	7.4 – 8.0	12.0 – 20.0
High	>8.0	>20.0

Table 6: Risk thresholds for Zebra Mussel Colonization (via: Murray et al. 1993, Biodrawversity 2013). Note: O'Neill 1996 classifies the range from 20-25mg/L as moderate risk.

Unfortunately, all of the average measurements for calcium (except in Squantz) are above the 20 mg/L threshold of moderate to high risk. This was not always the case in Candlewood, as calcium concentrations have been trending upward since monitoring began in 1992.

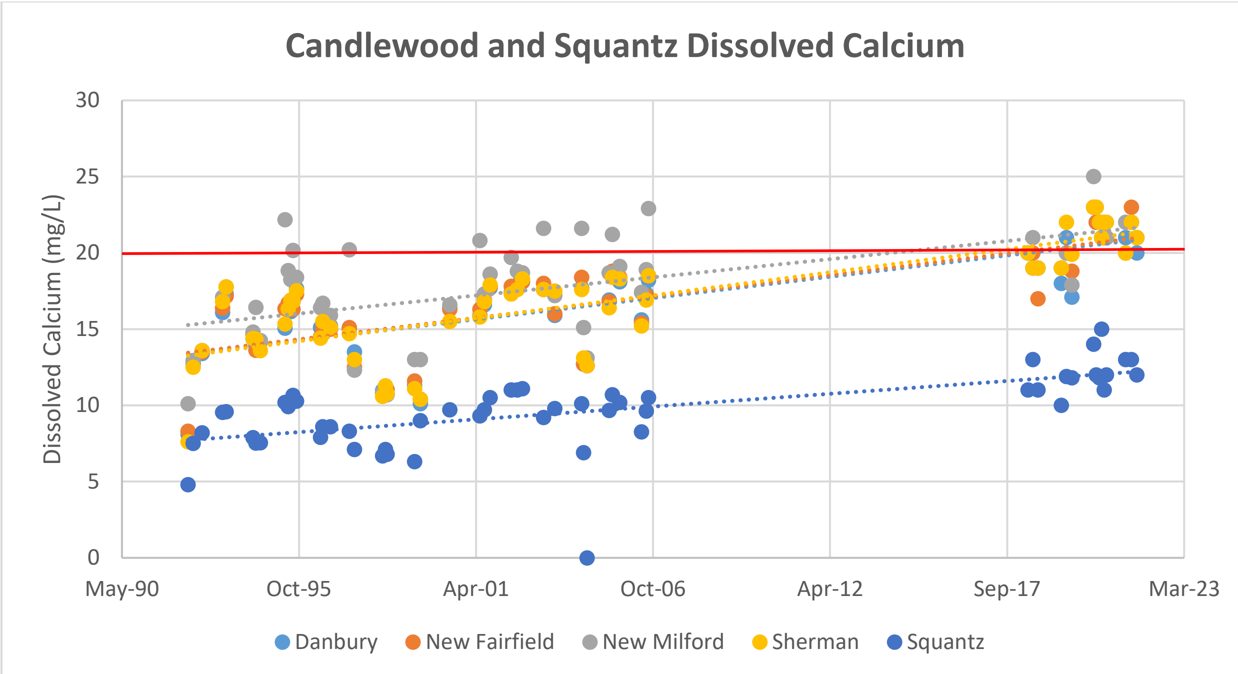


Figure 10: Calcium concentrations in Candlewood and Squantz since 1992. Note that missing data between 2006 and 2018 is still being re-organized and undergoing quality assurance, and will be included in future reports. The red line shows the "high" risk threshold for zebra mussel colonization.

This trend is concerning, but unsurprising, as calcium shows a strong correlation to conductivity in freshwater systems, meaning that as conductivity increases much of that increase is likely due to increases in dissolved calcium concentrations. We'd also like to work to keep Squantz Pond below high risk thresholds for zebra mussel colonization. Should zebra mussels colonize Candlewood, it will be interesting to see how efficiently they are able to spread into Squantz Pond where risk is low to moderate.

Zebra Mussel Monitoring

In May 2020, the first zebra mussel was found in Candlewood Lake by a diver off the tip of Vaughn's Neck in New Fairfield. This is in the main basin of Candlewood Lake, which is relatively surprising, as it is not near a usual vector for invasion (boat launch, natural stream, or housatonic river penstock). This spurred a more in depth search over the course of the next two summer and winter seasons. This search included:

1. Additional samplings for zebra mussel veligers using vertical net tows and cross-polar microscopy.
2. Shoreline searches during the drawdown by CLA employees, volunteers, and other organizations.
3. Zebra mussel "hotels" deployed by CLA employees and volunteers off of residential docks.
4. eDNA analysis of water samples by Dr. Wong's lab at Western Connecticut State University.
5. Dive searches from CLA volunteers and Biodrawversity.

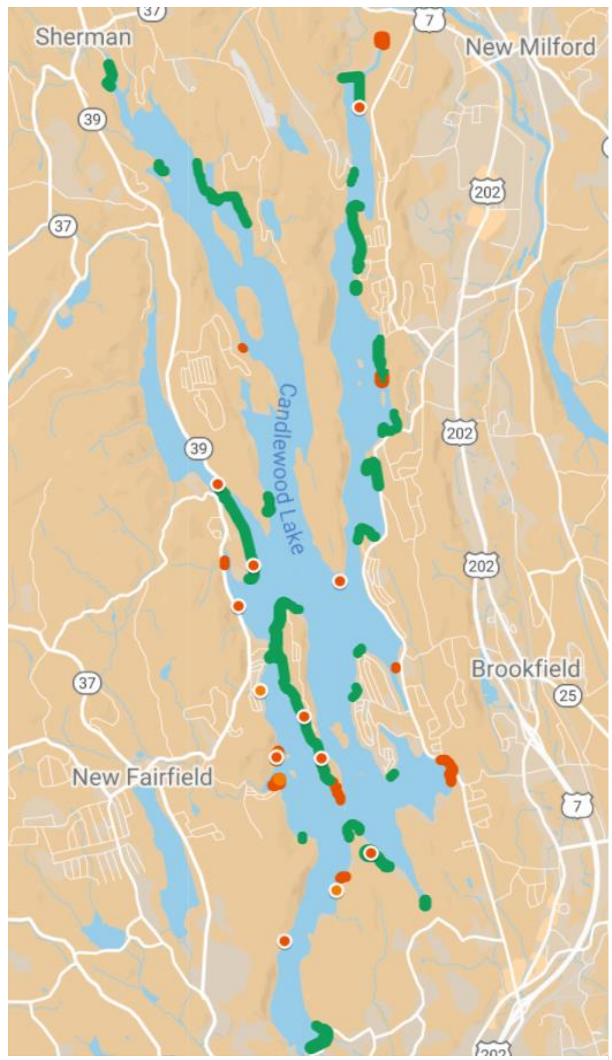


Figure 11: Map of Zebra Mussel Searches on Candlewood Lake. Green is searched shoreline with no mussels, and orange is locations with discovered mussels.

Since that first discovery in May of 2020, a total of 153 zebra mussels have been discovered in the lake following the 2021-22 winter drawdown. The mussels discovered cover a wide range of age classes, and include both juvenile and adult mussels, and their distribution in the lake is low density but widespread. This map illustrates all the locations (in orange) where mussels have been found so far.

All methods meant to find evidence of zebra mussel reproduction (veliger and eDNA analysis) have come back negative. That is to say, there is yet still no evidence apart from different mussel age classes that would indicate zebra mussel reproduction. This could mean that the population is simply too small for these methods to pick up the low levels of reproduction occuring in the lake, or that the population of zebra mussels is not reproducing successfully in the lake due to either a lack of upstream recruitment (no pumping from the Housatonic River during spawning season) or the moderately insufficient chemical measurements of dissolved calcium. It is still unclear whether or not the population in Candlewood lake is enough to fully establish and become a nuisance species that would impact recreational and environemental health of the lake, or if it will survive at low levels thanks to management via the drawdown and lack of upstream recruitment. We will continue the increased vigilence over the next 3 years to assess the trajectory of the population to get a better idea of the ultimate fate of the zebra mussel population in Candlewood Lake.

Discussion

2021 was a year of change for both the CLA's monitoring, and for Candlewood Lake. This marks the first year where the CLA was able to do two separate monitoring events per month for all of our key metrics. By increasing our samples per month and year, we can get a more accurate idea of the actual state of Candlewood Lake. We plan to continue this moving forward so that all of our measurements more closely approximate the true values in the whole lake, while also allowing us to see changes in the chemistry over time more accurately.

The lake itself also saw changes compared to last year – substantially higher chl-a and lower secchi clarity both point to a year marked by less pleasant recreational conditions. Despite this trend, nutrient concentrations in the epilimnion continue their meager decrease over time – a trend likely attributable to public education efforts and better community engagement. However, this trend might be slowing in recent years, so careful watch of nutrient level average change will be critical. The lake still shows strong internal loading tendencies during stratification, which can lead to strong algae blooms at the end of the season when the water column mixes, and those nutrients become available for use by the algal community. Salts and ions continue their concerning trend of growth, once again conductivity levels increased in the lake, and ions like calcium also continue their ascent.

Trophic Category	Total Phosphorus (µg / L)	Total Nitrogen (µg / L)	Summer Chlorophyll-*a* (µg / L)	Summer Secchi Disk Transparency (m)
Oligotrophic	0 - 10	0 - 200	0 - 2	>6
Early Mesotrophic	10 - 15	200 - 300	2 - 5	4 - 6
Mesotrophic	15 - 25	300 - 500	5 - 10	3 - 4
Late Mesotrophic	25 - 30	500 - 600	10 - 15	2 - 3
Eutrophic	30 - 50	600 - 1000	15 - 30	1 - 2
Highly Eutrophic	> 50	> 1000	> 30	0 - 1

Table 7: Eutrophication "report card" with 2021 average levels highlighted to illustrate the general eutrophic identity of the lake.

Candlewood generally remains a mid to late mesotrophic lake, meaning that most metrics point to the lake being "middle-aged" in the general lifespan of lakes. While Candlewood Lake is not an old lake, it is substantially impacted by the surrounding human development, precipitating higher nutrient measurements, lower clarity, and greener water. By working to lower nutrient levels in the lake, ideally we might begin to see improvements in chlorophyll-a and secchi disk measurements as well.

One of the most substantial changes in the lake's ecosystem in the past 2 years is the introduction of Zebra Mussels. While the population remains at relatively low levels, keeping tabs on any changes in their population growth is paramount. While they are distributed on a large enough scale that eradication is not an option, the viability of the population's long-term expansion remains unclear. Year-to-year growth seems to be generally stable, and there are yet no chemical signs of reproduction. By continuing and expanding efforts to monitor this population, we can more accurately evaluate whether the population is on course to become a nuisance species, or if it will continue to persist at low and more manageable levels. This will inform public education and community engagement projects, invasive species awareness for boaters, as well as future discussions with stakeholders about Housatonic River water pumping.

The general recommendations for the coming years based on these results are as follows:

1. Continue developing long-term monitoring strategies and remediation goals in a dedicated Candlewood Lake Management Plan (LMP).

2. Continue community education efforts surrounding phosphorus and nitrogen pollution to continue and strengthen downward trend.

3. Engage town public works and departments of transportation with a focus on efficient road salting to minimize lake impacts of road salt runoff.

4. Expand zebra mussel population monitoring efforts to decipher possible trajectories of the population and verify reproductive capacity.

5. Ensure lab is able to measure total nitrogen at levels necessary for in-lake chemical monitoring.

6. Continue twice monthly sampling and consider adding April to monitoring to catch early season information before stratification begins.